SSC-JE 2025

Staff Selection Commission

Junior Engineer Examination

Mechanical Engineering

Refrigeration and Air Conditioning

Well Illustrated **Theory** *with*
Solved Examples and **Practice Questions**

MADE EASY PUBLICATIONS

Refrigeration and Air Conditioning

Contents

CHAPTER 01

Introduction : Refrigerating Machine and Reversed Carnot Cycle

1.1 Introduction

- There are essentially two categories of thermal plants
  (i) Thermal power plants/work producing plants.
  (ii) Refrigeration or heat pump plants/work consuming plants.
- Work producing plants or heat engine lead to the conversion of heat to work.
- The objective of work consuming plant is to lead the flow of heat from a low temperature body to a high temperature body.
- Unit of Refrigerating Capacity is TR (Tonnes of Refrigeration)
  1 TR = Rate of removal of heat from 1 ton of water to freeze it into ice in 24 hr at 0°C = 50.4 kcal/min
- 1 kcal = 4.18 kJ
  Specific heat of water = 4.18 kJ/kgK
  Specific heat of ice = 2.11 kJ/kgK
  Specific heat of vapour = 1.99 kJ/kgK
  Latent heat of water
  in fusion = 335 kJ/kg (at 0°C)
  in vapourization = 2260 kJ/kg (at 100°C)

NOTE

Methods of Production of Low Temperatures

(i) Throttling expansion of liquid with flashing

(ii) Reversible adiabatic expansion of gas

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

(iii) Irreversible adiabatic expansion of real gas

$$\left(\frac{\partial T}{\partial P}\right)_h = \delta \text{ or } \mu_J$$

This process is known as throttling an μ_J is called Joule Thomson coefficient.

(iv) Thermoelectric effect or Peltier effect : Cooing of one junction and the healthy of other junction, when electric current is passed through the circuit of dissimilar metals (conductors).

1.2 A Refrigerating machine - The second law interpretation

- A refrigerating machine is a device which will either cool or maintain a body at a temperature below that of the surroundings.
- Schematic Diagram of Refrigerating/AC machine with temperature is shown.
- The cooled space is to be maintained at 15°C. The refrigerating machine takes the air at 25°C, and due to evaporation of refrigerant, heat is taken from the air which is cooled to 15°C and returned back to cooled space. During compression, the temperature rises to 65°C while outside temperature is 45°. Hence heat is transferred to outside air while the refrigerant is condensed and temperature of outside air is raised. This condensed/liquid refrigerant is expended by a throttling device and temperature lowers again to 5°C.

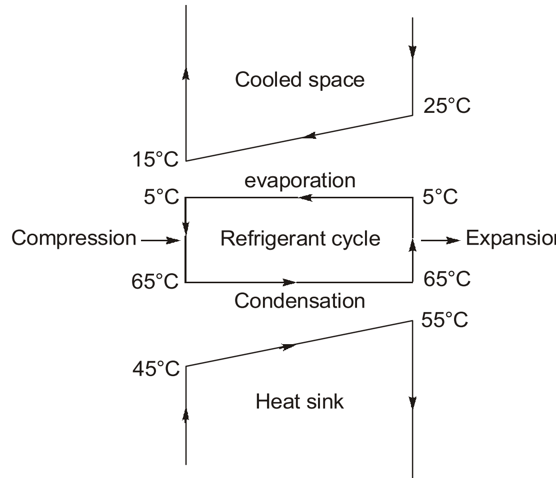


Figure 1.2

Units in Refrigeration

$$1 \text{ cal} = 4.1868 \text{ Joule (J)}$$
$$1 \text{ horse power} = 746 \text{ Watt (W)}$$
$$1 \text{ unit of power} = 1 \text{ kWH} = 3600 \text{ kJ} = 860 \text{ K cal}$$
$$1 \text{ TR (ton refrigeration)} = 50 \text{ K cal/min} = 3.5167 \text{ kW} = 211 \text{ kJ/min.}$$

Properties of Air

$$C_P = 1.005 \text{ kJ/kgK}$$
$$C_V = 0.718 \text{ kJ/kgK}$$
$$R = 0.287 \text{ kJ/kgK}$$
$$\gamma = 1.4$$
$$M = 28.966 \text{ g/mol or kg/kmol}$$

Example 1.1 In a 3 ton capacity water cooler, water enters at 30°C and leaves at 15°C steadily, what is the water flow rate per hour?

(a) 60 kg (b) 100 kg
(c) 602 kg (d) 2520 kg [IES : 2013]

Solution: **(c)**

In steady state, heat absorb from water is equal to the capacity of water cooler.

$$3 \text{ ton} = 3 \times 3.5 \text{ kJ/s} = 3 \times 3.5 \times 3600 \text{ kJ/hr} = 37800 \text{ kJ/hr}$$

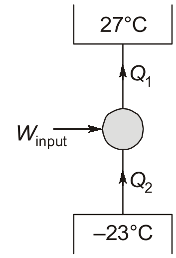
Now, $$37800 = \dot{m} C_p \Delta T$$

$\Rightarrow$ $$\dot{m} = \frac{37800}{4.18 \times 15} = 602.87 \text{ kg/hr}$$

Example 1.2 A refrigerator operates between the temperature –23°C and 27°C. If one TR = 3.5 kW, the minimum power required per TR to operate the refrigerator is __________.

(a) 0.5 kW (b) 0.7 kW
(c) 0.9 kW (d) 1 kW [ESE : 2010]

Solution: **(b)**



$$COP_R = \frac{T_L}{T_H - T_C} = \frac{250}{300-250}$$

For minimum power requirement/TR

$$\frac{1 \times 3.5}{W_{min}} = \frac{250}{300-250}$$

$\Rightarrow$ $$W_{min} = 0.7 \text{ kW}$$

1.3 Refrigerating Machine/Heat Pump

- It is consist of evaporator, compressor, condenser, expander.
- The processes involved in the cycle are as follows:
  - Heat Q_0 is absorbed in the evaporator by the evaporation of a liquid refrigerant at a low pressure P_0 and corresponding low saturation temperature T_0.
  - The evaporated refrigerant vapour is compressed to a high pressure P_k in the compressor consuming work W.
  - Heat Q_k is rejected from the condenser to the surrounding.
- When refrigerating machine is used for cooling the space, it is called refrigerator. When the machine is used for heating the space, it is called heat pump.

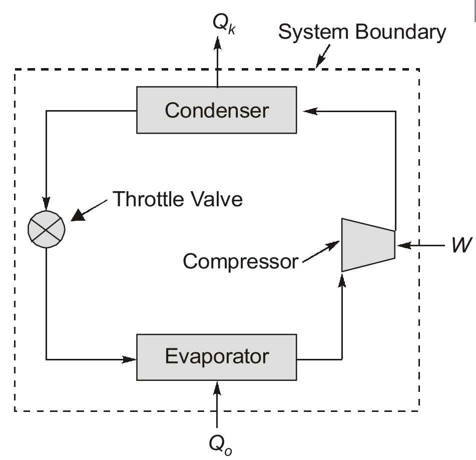


Figure 1.3

- Same machine can be used either for cooling or for heating. The main difference between the two is in their operating temperatures.
- A refrigerating machine operates between the ambient temperature and a low temperature. A heat pump operates between the ambient temperature and a high temperature.
- Another essential difference is in their useful functions. In a refrigerating machine the heat exchanger that absorbs heat is connected to the conditioned space. In a heat pump, the heat exchanger that rejects heat is connected to the conditional space.

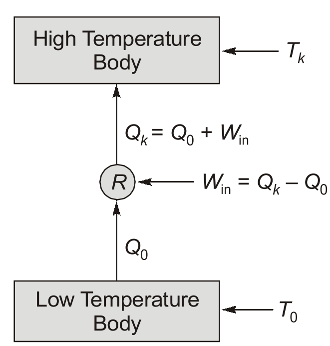


Figure 1.4

1.4 Coefficient of Performance (COP) or Energy Ratios

$$COP = \text{Energy Ratio} = \frac{\text{useful heat}}{\text{work}}$$

$$(COP)_{ref} = \frac{Q_0}{W} = \frac{Q_0}{Q_k - Q_0}$$

$$(COP)_{pump} = \frac{Q_k}{W} = \frac{Q_k}{Q_k - Q_0} = 1 + \frac{Q_0}{Q_k - Q_0}$$

$\therefore$ $$(COP)_{pump} = 1 + (COP)_{ref}$$

- If refrigerator/heat pump cycle is reversed, it becomes a heat engine.
- Thermal efficiency of heat engine

$$\eta_{th} = \frac{W}{Q_k} = \frac{Q_k - Q_0}{Q_k}$$

$$(COP)_{pump} = \frac{Q_k}{Q_k - Q_0} = \frac{1}{\eta_{th}}$$

$$(COP)_{ref} = \frac{1}{\eta_{th}} - 1 = \frac{1-\eta_{th}}{\eta_{th}}$$

$$\text{Energy efficiency ratio, EER} = \frac{\text{Output cooling energy (BTU)}}{\text{Input electric energy (Wh)}} = COP \times 0.293$$

NOTE

- COP of Different Vapour Compression System

Type of vapour Compression System	COP
Water cooled	3
Air cooled	2
Domestic Refrigerator	1
Vapour absorption system	<1

- Power consumption of a refrigerator/heat pump

$$1 \text{ H.P.} = \frac{\dot{W} \text{ (in kW)}}{0.746}$$

Refrigerating capacity,

$$(TR) = \frac{Q_0 \text{ (in kW)}}{3.5167}$$

$$\frac{HP}{TR} = \frac{\dot{W}}{0.746} \times \frac{3.5167}{\dot{Q}_0} = 4.71\frac{\dot{W}}{Q_0} = \frac{4.71}{(COP)_{Ref}}$$

where, $\dot{W}$ is power consumption (kW) ; Q_0 is refrigerating effect (kW).

Example 1.3 The food compartment of a refrigerator is maintained at 4°C by removing heat from it at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, the COP of the refrigerator is :

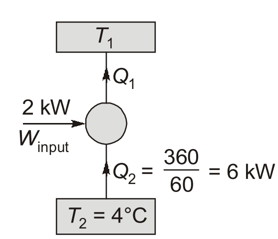
(a) 2.0 (b) 1/3
(c) 0.5 (d) 3.0

[SSC-JE : 2014]

Solution: **(d)**

$$COP_R = \frac{Q_2}{W_{input}}$$

$$= \frac{6}{2} = 3$$

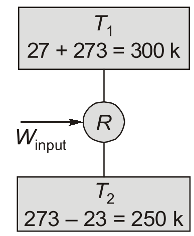


Example 1.4 A refrigeration cycle operates between condenser temperature of +27°C and evaporator temperature of –23°C. The Carnot coefficient of performance of cycle will be ______.

(a) 0.2 (b) 1.2
(c) 5 (d) 6

[SSC-JE : 2017]

Solution: **(c)**



$$COP_R = \frac{T_2}{T_1 - T_2}$$

$$= \frac{250}{50} = 5$$

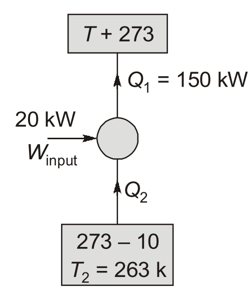
Example 1.5 A Carnot heat pump is used to maintain a room at a temperature of T°C, the initial temperature of the room was –10°C. If the power requirement of the pump is 20 kW and the heat provided to the room is 150 kW. What will be the value of T?

(a) 0 (b) 30
(c) 303 (d) Cannot be determined

[SSC-JE : 2018]

Solution: **(b)**

For reversible HP,



$$COP = \frac{T + 273}{T + 10}$$

Also, $$COP_{HP} = \frac{Q_2}{W_{input}} = \frac{150}{20} = 7.5$$

So, $$7.5 = \frac{T + 273}{T + 10}$$

$\Rightarrow$ $$T = 30.46°C \approx 30°C$$

Example 1.6 If the efficiency of a Carnot engine is 40%. Then the COP of the Carnot refrigerator will be ________.

(a) 1 (b) 1.5
(c) 2.5 (d) 3

[SSC-JE : 2018]

Solution: **(b)**

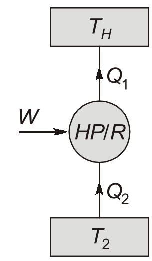
$\eta_E = 0.4 \Rightarrow$ $$COP_{HP} = \frac{1}{\eta_E} = \frac{1}{0.4} = 2.5$$

But $$COP_R = COP_{HP} - 1 = 2.5 - 1 = 1.5$$

Example 1.7 A refrigerator working on a reversed Carnot cycle has a COP of 4. If it work as a heat pump and consumes 1 kW, the heating effect will be

(a) 1 kW (b) 4 kW

(c) 5 kW (d) 6 kW



***Solution:* (c)**

$$(COP)_{HP} = 1 + COP_R$$

$$\frac{Q_1}{W} = 1 + 4$$

$$Q_1 = 5\,W = 5 \times 1 = 5\text{ kW}$$

1.5 Heat Pump vs. Electric Resistance Heater

- If 'W' is the energy consumption in electric resistance heater, its output is equal to W.
- If 'W' is the energy consumption of heat pump. Its output, $Q_k = (COP)_{pump} W = (1 + COP_{ref})W$
  - COP_{ref} varies from 0 to ∞.
  - COP_{pump} varies from 1 to ∞.
  - When refrigeration/Heat pump cycle is reversed carnot cycle

$$(COP)_{ref} = \frac{Q_0}{Q_k - Q_0} = \frac{T_0}{T_K - T_0}\ ; \quad (COP)_{pump} = \frac{Q_k}{Q_k - Q_0} = \frac{T_k}{T_K - T_0}$$

  - For high COP for refrigerator or heat pump
  - T_0 should be as high as possible
  - T_K should be as low as possible
  - Water is a better cooling medium than air (i.e. higher COP & lower power consumption for water in refrigerator) because,

    T_0 = Evaporator ; T_k = Heat rejection temperature
  - Specific heat of water is about four times that of air. [For same heat output (Q_k) rise in water temperature is lower than air temperature (i.e. low T_k)].
  - Water has high thermal conductivity than air. So for same temperature difference of (refrigerant and air) and (refrigerant & water), more heat can be transferred in water system.
  - So for small refrigeration system (A.C., domestic refrigerator), air as cooling medium is used.
  - For big refrigeration system (central A.C., ice plant, cold storage) water as cooling medium is used.

1.6 Vapour as Refrigerant in a Reversed Carnot Cycle

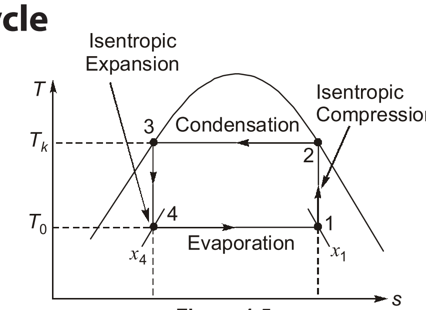


Figure 1.5

For Per Unit Mass of Vapour

Refrigerating effect $= q_0 = h_1 - h_4$

Heat reject $q_m = h_2 - h_3$

Compressor work w_c (consumed) $= h_2 - h_1$

Expander work w_e (gained) $= h_3 - h_4$

Net work $= w_c - w_e = (h_2 - h_1) - (h_3 - h_4)$

$$(COP)_{Ref} = \frac{q_0}{w} = \frac{h_1 - h_4}{(h_2 - h_1) - (h_3 - h_4)} = \frac{h_1 - h_4}{(h_2 - h_3) - (h_1 - h_4)}$$

1.6.1 Draw Back of Using Vapour as Refrigerant in Reversed Carnot Cycle

1. Liquid refrigerant may be trapped in heat of cylinder and damage the compressor valves.
2. Liquid droplets may wash away the lubricating oil from the walls of compressor cylinder.
3. Expander is costly and the work gained in expander is not significant.
   - The Carnot cycle is the most efficient between the given temperature limits (T_k and T_0)
   - Second law efficiency or exergetic efficiency for cooling or heating is $(\eta_{II}) = \dfrac{(\text{COP})_{\text{actual}}}{(\text{COP})_{\text{Carnot}}}$
   - Other than this, in reverse carnot cycle isentropic process requires very high speed operation, where as isothermal process requires very slow speed.

1.7 Gas as Refrigerant in Reversed Carnot Cycle

Refrigerating effect,

$$q_0 = q_{4-1} = RT_0 \ln\frac{v_1}{v_4}$$

Net work = (W_{2-3}) − (W_{4-1})

(W_{2-3}) ↓ consumed in compressor; (W_{4-1}) ↓ gained from expander

[(W_{1-2}) and W_{3-4} are same and opposite in sign. So they cancel each other.]

$$\text{Net work} = RT_k \ln\frac{v_2}{v_3} - RT_0 \ln\frac{v_1}{v_4}$$

$$= R(T_k - T_0)\ln\frac{v_1}{v_4} \qquad \left[\because \frac{v_2}{v_3} = \frac{v_1}{v_4}\right]$$

$$(\text{COP})_{\text{Ref}} = \frac{q_0}{w} = \frac{T_0}{T_k - T_0}$$

$$= \frac{1}{\left(\frac{T_k}{T_0}\right) - 1} = \frac{1}{r^{\gamma-1} - 1} \qquad \left[\because r = \frac{v_1}{v_2} = \frac{v_4}{v_3} = \left(\frac{T_k}{T_0}\right)^{\frac{1}{\gamma-1}}\right]$$

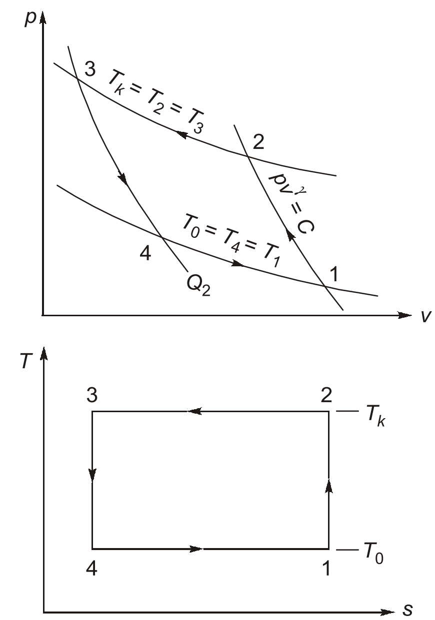


Figure 1.6

1.7.1 Draw Back of using Air as Refrigerant in Reversed Carnot Cycle

- Isothermal process of heat absorption and rejection being very slow and is not possible practically.
- *P*-*v* diagram for gas is very narrow so very high stroke volume is needed to have desired refrigerating effect.

STUDENT'S ASSIGNMENTS

Q.1 In a certain ideal refrigeration cycle, the COP of heat pump is 5. The cycle under identical conditions running as heat engine will have efficiency as
(a) Zero (b) 0.20
(c) 1.00 (d) 6.00

[IAS : 2001]

Q.2 The power (kW) required per ton of refrigeration is *N*/COP, where COP is the coefficient of performance, then N is equal to
(a) 2.75 (b) 3.50
(c) 4.75 (d) 5.25

[IAS : 2001]

Q.3 A refrigerator works on reversed Carnot cycle producing a temperature of –40°C. Work required per TR is 700 kJ per ten minutes. What is the value of its COP?
(a) 3 (b) 4.5
(c) 5.8 (d) 7

[IES : 2005]

Q.4 A reversed Carnot cycle working as a heat pump has COP of 7. What is the ratio of minimum to maximum absolute temperature?
(a) $\frac{7}{8}$ (b) $\frac{1}{6}$
(c) $\frac{6}{7}$ (d) $\frac{1}{7}$

[SSC-JE : 2018]

Q.5 The COP of a refrigerator on a reversed Carnot cycle is 5. The ratio of higher absolute temperature to the lower temperature (i.e., T_2/T_1) is
(a) 1.25 (b) 1.3
(c) 1.4 (d) 1.2

[IAS : 2003]

Q.6 A refrigerating machine working on reversed Carnot cycle takes out 2 kW of heat from the system at 200 K while working between temperature limits of 300 K and 200 K. COP and power consumed by the cycle will, respectively, be
(a) 1 and 1 kW (b) 1 and 2 kW
(c) 2 and 1 kW (d) 2 and 2 kW

[IAS : 2004]

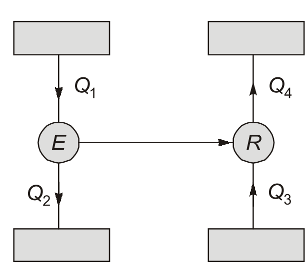
Q.7 A refrigerating machine in heat pump mode has a COP of 4. If it is worked in refrigerator mode with power input of 3 kW, what is the heat extracted from the food kept in the refrigerator?
(a) 180 kJ/min (b) 360 kJ/min
(c) 540 kJ/min (d) 720 kJ/min

[IAS : 2006]

Q.8 A refrigerator storage is supplied with 3600 kg of fish at a temperature of 27°C. The fish has to be cooled to –23°C for preserving it for a long period without deterioration. The cooling takes place in 10 hours. The specific heat of fish is 2.0 kJ/kgK above freezing points of fish and 0.5 kJ/kgK below freezing point of fish, which is –3°C. The latent heat of freezing is 230 kJ/kg. What is the power to drive the plant if the actual COP is half that of the ideal COP?
(a) 30 kW (b) 15 kW
(c) 12 kW (d) 6 kW

[IAS : 2002]

Q.9



In the figure shown above, *E* is the heat engine with efficiency of 0.4 and *R* is the refrigerator. If $Q_2 + Q_4 = 3Q_1$, the COP of the refrigerator will be
(a) 3.0 (b) 4.5
(c) 5.0 (d) 5.5

[IES : 2014]